Proceedings of the International Conference of Recent Trends in Environmental Science and Engineering (RTESE'17)
Toronto, Canada – August 23 – 25, 2017
Paper No. 139
DOI: 10.11159/rtese17.139

Plant-Wide Simulation for a Mega WWTP: A Case Study of Gabal El-Asfar WWTP, Egypt

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Abstract **-** Modeling of wastewater treatment plants (WWTPs) has proven itself as a very useful tool for understanding and optimizing wastewater processes. A validated model can be quite beneficial in terms of cost saving due to the prediction of the outcome of various operation scenarios and choosing the optimum operation strategy. In this paper, BioWin model (Envirosim, Canada) was used to describe the performance of an Egyptian wastewater treatment plant located in Cairo, Egypt. Gabal El-Asfar WWTP is a mega WWTP, the largest in Africa and the Middle East, and receiving municipal wastewater. Applying the Good Modeling Practice (GMP) protocol showed clear organized steps for successful modeling of Gabal El-Asfar WWTP. Historical data and design reports have been collected and various site visits have been made besides a detailed sampling campaign to perform a proper wastewater characterization and a successful model calibration. The model calibration was performed under steady-state conditions by adjusting seven stoichiometric and kinetic parameters: heterotrophic maximum growth rate, heterotrophic aerobic decay rate, substrate half saturation, maximum AOB growth rate, AOB decay rate, NH_4 substrate half saturation, and finally maximum NOB growth rate. The model was calibrated and validated using BioWin v.5.2 software. The BioWin model was successfully used for creating a plant-wide model for Gabal El-Asfar WWTP with accuracy high enough to perform plant optimization in further studies.

Keywords**:** biological treatment, BioWin, mathematical modeling, wastewater, plant-wide simulation.

1. Introduction

Wastewater contains high concentrations of carbonaceous and nitrogenous organic matter which considered among main water pollutants. Therefore, wastewater must be treated prior to discharge to the environment [1]. Wastewater biological treatment is a vital aspect of public health. There are different types of processes in wastewater treatment. Among them and considered the most applied method is the activated sludge process as it is considered a very effective and a common way of removing contaminants from wastewater. Activated sludge is a secondary wastewater treatment process used to remove organic matter and nutrients from wastewater.

For the purpose of designing and operating activated sludge systems many activated sludge models have been developed and applied. An activated sludge model is a representation of the processes of microbial growth and substrate utilization growth within an activated sludge system through a dynamic mathematical expression [2]. Activated sludge modeling is a useful tool for optimizing wastewater processes, it allows researchers and operators to understand the effect of different changes within the process operation, optimize, predict the expected results, and develop control strategies for the WWTPs. ASM Models are widely used in the optimization studies for the existing WWTPs and development of control strategies for both new and existing WWTPs [3].

Anaerobic digestion is also a commonly used process for sludge treatment to minimize their negative environmental effect. Besides producing stabilized solids, another useful by-product from anaerobic digestion is methane gas (CH4) that can be used for energy production. Generally anaerobic digestion in the microbiological, biochemical and technological point of view is composed of four major steps that can be summed up as following: hydrolysis, acidogenesis, acetogenesis and methanogenesis [4]. Anaerobic digestion modelling process can follow the time evolution of the biogas produced composition during the organic matter transformation. Hydrolysis step is the step where substrate is solubilized through the exerted extracellular enzymes from certain bacterial types. Hydrolysis is not considered a biological process as no metabolism takes place, on the other hand acidogenesis, acetogenesis and methanogenesis are considered metabolic steps due to the substrate consumption and conversion by bacteria. Digestion biokinetics can be described by three phenomena: substrate consumption, growth and bacterial decay, methane production and inhibition of bacterial activity [5].

The availability of a plant-wide model for a WWTP allows the study of the influence of the different operational parameters such as temperature and sludge retention time on effluent quality and helps in developing a plan to reach a high level of? nutrient removal in parallel with a cost saving strategy for energy consumption through running different scenarios on the calibrated model. In plant-wide models, WWTP are thought of and treated as a system that is completely integrated, where primary settlers and final clarification units, biological reactors, sludge digester units, sludge thickening units, sludge dewatering systems and any other related processes are linked together. All those processes are not operated and controlled as individual processes on a localized level yet all interactions between the different processes are taken into account. The development of plant-wide modeling in the wastewater treatment field is very attractive to many researchers since it provides an overall view of the processes included in the treatment so it provides a more comprehensive understanding of the many complicated interactions between the various unit processes [6].

BioWin© software and model (Envirosim, Canada) are one of the famous simulators that has its own general activated sludge-digestion model (AS/DM). It allows modelers to model different treatment processes without the coupling of more than one model. BioWin is recognized by IWA and used worldwide. The model has many useful features which are extremely useful for modeling and optimization of complicated water treatment systems [7, 8]. There are 50 state variables and 60 process expressions included in the BioWin general model. BioWin as a simulator is considered a highly beneficial general purpose simulator that accomplishes high models combination flexibility, yet it also leads modelers to consume long times in order to construct a specific WWTP model [9]. Therefore, appropriate wastewater characterization for the influent such as the definition of influent COD and nitrogenous fractions and adequate model calibration in terms of adjusting kinetic and stoichiometric parameters to predict the same effluent characteristics of the actual plant are needed to create a reliable model that can describe the full- scale WWTP observations accurately [10].

The Egyptian Wastewater Treatment Plant namely Gabal El-Asfar (GAWWTP) in Cairo, the case study for this paper, is one of the largest WWTPs in the world, considered the largest in Africa and the Middle East and one of the few plants that successfully applies sludge anaerobic digestion in Egypt [11]. GAWWTP is a mega WWTP which treats both wastewater and sludge and is of a great importance to the Egyptian sanitation. It discharges its treated effluent to "Bahr EI Baqar" drain which flows for approximately 170 km from Cairo governorate to Lake Manzala. The Egyptian Environmental Action Plan Identified Manzala Lake and Bahr EI-Baqar drain system as "black spots". Different operational routines for GAWWTP have to be deeply investigated and multiple optimization alternatives have to be proposed for the purposes of operational cost minimization while maintaining the required effluent quality. In this study, the main objective is to develop a plant-wide model to describe the current performance of Egypt's largest WWTP "GAWWTP" using BioWin activated sludge model. Then, the model will be used in a further study to develop a process plan to achieve full nutrient removal in GAWWTP taking into consideration energy consumption and production.

2. Material and Methods

In the last decade, several guidelines have been developed around the world that focuses on different simulation projects aspects projects such as BIOMATH, WERF, STOWA, HSG, and good modeling practice (GMP) [12]. GMP protocol was followed for the modeling of GAWWTP in this study. The GMP Task Group comprises the following main steps: definition of the project, collection of data, setup of plant model, calibration and validation, simulation and finally interpretation of the results.

2.1. GAWWTP Process Description

GAWWTP, the case study for this paper, consists of different stages. This study focuses on modeling and optimization of "Gabal El-Asfar - contract 19" stage. This stage is an activated sludge WWTP with a 500,000 m^3/day capacity. The WWTP consists of 6 Circular Primary settling tanks with a diameter of 53 m each, it has 8 biological tanks of a total volume 109,840 m3 and 4 days SRT. The Aeration tanks in GAWWTP "Contract 19" consist of three-zone circular aeration tank, including a central zone (divided into two zones) and an external zone. The central zone of the aeration tanks which corresponds to 1/3 of the aeration volume is receiving 50 % of oxygenation capacity and is full time aerated in order to eliminate 70 to 80 % of the pollution. After that, the flow is directed to the external zone corresponding to 2/3 of the aeration volume and receiving 50 % of oxygenation capacity and can be aerated or non-aerated to control nitrification phenomena which usually occur during summer time. Submersible mixers which are running on a full-time basis, are installed in the external zone of each tank to ensure a good mixing in the reactor and to avoid settling during non-aerated period. Flexibility of operation has been provided in the central zone as the 1st part can be used as an anoxic zone by stopping the injection of air in this part. At the outlet weir of each AT, a sufficient water fall facilitates the air bubbles elimination to avoid possible sludge floating phenomena in the final clarifier. The sludge extracted from each final clarifier tank is directed to the return activated sludge pumping station. The design sludge recycling rate is 100 % of the average flow (500,000 m3/d). The WWTP has 6 secondary clarifiers with 52 m diameter each and water depth of 3.9 m. The treated water coming from the final clarifiers stream is directed to chlorination tanks for chlorine injection before final disposal.

The WWTP is equipped with a sludge treatment system consists of dissolved air floatation tanks to treat the secondary sludge and gravity thickeners to treat the primary sludge. Thickened sludge from the thickened sludge pumping station and floated sludge from DAF unit are directed to the sludge digestion facilities. The WWTP has 8 primary anaerobic digesters each having a volume of 9760 m3 plus 2 secondary digesters each having a volume of 8753 m3. The primary sludge digester tanks are mixed by means of recycled biogas and heated by means of external heat exchangers in the boiler and heater house. The primary digested sludge then gravitates to secondary sludge digesters for final digestion. The secondary sludge digester tanks are mixed by means of recycled biogas. Sludge gas is stored in the gas holder and piped to the boiler house, the dual fuel generating station and the gas flare stack. The gas needed for the mixing of the digesters is not passing by the gas holder and is recycled directly. Moreover, the WWTP contains a dewatering house which consists of 12 belt press filters, the unit width is 3 m, and are installed in 4 lines of 3 machines each: 10 on duty and 2 on stand-by. Figure 1 shows a satellite image of the treatment plant.

Fig. 1: GAWWTP “contract 19” satellite image.

2.2. Historical Analysis and Sampling Campaign

In GAWWTP contract 19, wastewater flows are measured on-line whereas most of the other measurements are done in the lab. The routinely measured data over the last 3 years were obtained from the plant operator. The plant is operated by

DEGREMONT and has a restricted quality control for measurements. All samples routinely taken by the operator are composite. Although measuring precision is high, measuring accuracy is unknown. Based on the historical wastewater analysis, it can be concluded that the monthly average inlet flow was above 500,000 m^3/d at all time, reaching 504,892 m3/d on yearly average. PST efficiency is high, stable and reaches 69% for SS removal and 56% for BOD5 removal. According to the plant operators, the concentration of MLSS in the aeration tanks is around 1.17 g/l in average. The daily parameters of the treated wastewater are all the time under the guarantee limit of 30 mg/l for SS and BOD5 on daily composite samples. The average values for S.S and BOD5 are 7.9 mg/l and 10.3 mg/l which means 96.1% for SS and 94.3% for BOD5 removal efficiency with a great stability.

Some of the necessary analysis required for the calibration step was not performed in the plant, hence, an external sampling campaign has been made. After the approval of the Egyptian authorities, a detailed sampling campaign was conducted by the researchers for five consecutive days in November 2016, for the purpose of wastewater characterization and calibration. For the sampling campaign 24 hours-composite samples were used for raw water influent, primary effluent and final treated effluent, while the rest of the measurements were performed using four grab samples due to insufficient tools and resources. During the course of the sampling program the weather was favourable. There was no rainfall and the plant was operated at dry weather conditions at an average air temperature of 24ºC.

The samples were analysed to examine the parameters, including the total chemical oxygen demand (COD), filtered COD, total Kjeldahl nitrogen (TKN), volatile suspended solids (VSS), total suspended solids (TSS), alkalinity, ammonium (NH4-N), nitrate (NO3-N), orthophosphates (PO4-P), temperature (T), dissolved oxygen and pH. All the measurements were based on the standard methods [13]. STOWA guidelines for influent characterization was the basis for the characterization of the different flows [14]. Table 1 shows the most important average values for the influent and effluent obtained during the sampling campaign. MLSS in the aeration tanks was 1,312.3 ± 33.5 mg/l, while MLVSS was 953.3 ± 53.1 mg/l.

BioWinv.5.2 (Envirosim, Canada) was used as a simulation platform for performing the wastewater treatment plant modeling. Using the data obtained from the sampling campaign and routinely measured data, the model was calibrated and validated, with modifications to the most sensitive parameters.

Table 1: Raw Influent and Effluent Sampling Campaign Analysis Results.

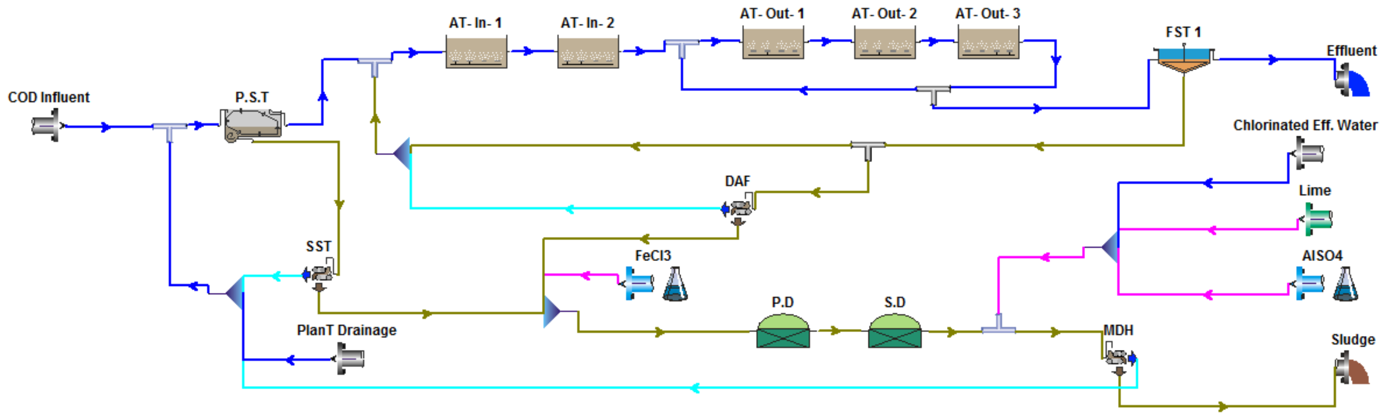
Parameter	Unit	Influent	Effluent
Flow	m^3/d	502,380±930	532055±1948
COD	mg/l	274.7	26.9 ±5.5
Filtered COD	mg/l	109.9	23± 3.6
Acetate	mg/l	8.3 ± 3.9	-
$cBOD_5$	mg/l	146.7	11±0.8
Filtered $cBOD_5$	mg/l	60.0	-
TSS	mg/l	202.7	8.1 ± 0.5
VSS	mg/l	127.3	5.9 ±0.3
TKN	mg/l	32.67	16 ±1.3
NH_4-N	mg/l	21.03	12.4±1.1
PH	-	7.09	7.07
Temp	°C	24 ± 0.3	

3. Results and Discussion

3.1. Wastewater Characterization

The data obtained from the sampling campaign has been compared with historical data in order to characterize the influent flow to the wastewater treatment plant. For the flow characterization, the average flow from five days of sampling campaign was used. Influent characterization has been performed according to the STOWA protocol for characterization. Table 2 shows the characterization parameters for raw wastewater and its default values.

DOI: 10.11159/rtese17.139



- PST : Primary Sedimentation Tanks
- AT : Aeration Tanks
- FST : Final Settling Tanks
- STT : Sludge Thickening Tanks
- DAF : Dissolved Air Flotation
- P.D : Primary Digesters
- S.D : Secondary Digester
- MDH : Mechanical Dewatering House

Fig. 2: Plant wide BioWin model Layout for GAWWTP “contract 19”.

Table 2: Characterization parameters for Raw wastewater.

Parameter	Units	BioWin Default Value	Calculated Value
Fbs - Readily biodegradable (including Acetate)	gCOD/g of total COD	0.16	0.1049
Fac - Acetate	gCOD/g of readily biodegradable COD	0.15	0.2883
Fxsp - Non-colloidal slowly biodegradable	gCOD/g of slowly degradable COD	0.75	0.8262
Fus - Unbiodegradable soluble	gCOD/g of total COD	0.05	0.030
Fup - Unbiodegradable particulate	gCOD/g of total COD	0.13	0.0583
Fna - Ammonia	gNH_3-N/gTKN	0.66	0.4583
Fnox - Particulate organic nitrogen	gN/g Organic N	0.5	0.5
Fnus - Soluble unbiodegradable TKN	gN/gTKN	0.02	0.02
FupN - N: COD ratio for unbiodegradable part. COD	gN/gCOD	0.035	0.035
Fpo4 - Phosphate	gPO_4-P/gTP	0.5	0.5
FupP - P: COD ratio for influent unbiodegradable part. COD	gP/gCOD	0.011	0.011

3.2. BioWin Plant-Wide Model

The Plant-wide model simulates the primary settlers, biological aeration tanks, final clarifiers, gravity thickener, dissolved air floatation, anaerobic digesters and the mechanical de-watering of GAWWTP “contract 19”. The raw wastewater characterization was used in this model. This model simulates the full plant and is the core of the modeling study and will be used in the plant optimization. Figure 2 shows the BioWin v.5.2 platform layout for the plant-wide model.

3.3. Model Calibration

The plant-wide model is calibrated mainly according to the STOWA protocol. Before the calibration step, the BioWin models are simulated using the default kinetic and stoichiometric values. Using the data acquired from the sampling campaign. Organic-Nitrogen factors are adjusted to match with measured influent TKN and NH_3-N. Then the inert particulate COD (XI) was adjusted to match the model predicted sludge production (VSS & TSS) of the aerations with the measured values. SRT is calculated based on the model predicted values.

Then the stoichiometric and kinetic parameters were calibrated with the aid of the sensitivity analysis performed by (Liwarska-Bizukojc & Biernacki, 2010) [8]which defined the most influential stoichiometric and kinetic parameters used to calibrate a BioWin model. Nitrification process is calibrated to match the measured effluent ammonia by adjusting the decay factor of autotrophic biomass and the substrate (NH_4) half saturation factor (KNH_4). Denitrification process is calibrated to match the measured effluent nitrate by adjusting the anoxic hydrolysis factor (ηNO_3) and anoxic NO_3 half saturation factor (KNO_3). Finally, effluent soluble inert COD is calibrated by adjusting the influent soluble inert COD (SI). Table 3 shows the calibrated stoichiometric and kinetic parameters in BioWin software.

3.4. Model Validation

The calibrated model was validated using the acquired data from the plant for the month September 2016. That period was chosen where no rehabilitation processes were planned also no operational problems occurred. Moreover, the temperature during the time where the data for validation was acquired is different from the temperature during acquiring the data for validation. Table 4 shows the most important average values for the influent, effluent, and simulated effluent parameters acquired from BioWin software. Table 5 shows the measured sludge production from the different treatment processes and simulated values acquired from BioWin software.

Table 3: Calibrated stoichiometric and kinetic parameters in BioWin v.5.2.

Parameter	**BioWin Default**	**Calculated Value**
Heterotrophic Bacteria (OHO)		
Max. spec. growth rate [1/d]	3.2	2.4
Substrate half sat. [mg COD/L]	5	15
Aerobic decay rate [1/d]	0.62	0.75
Ammonia Oxidizing Bacteria (AOB)		
Max. spec. growth rate [1/d]	0.9	0.5
Substrate (NH_4) half sat. [mg N/L]	0.7	1.5
Nitrite Oxidizing Bacteria (NOB)		
Max. spec. growth rate [1/d]	0.7	0.5
Substrate (NO_2) half sat. [mg N/L]	0.1	1.5

Table 4: Model validation of the plant performance based on average monthly results for September, 2016

Parameter	Unit	Influent	Measured Effluent	Simulated effluent
TSS	mg/l	186.1 ± 30.5	7.4 ± 1.1	8.02
COD	mg/l	280.8 ± 32.2	30.6 ± 6.5	28.60
$cBOD_5$	mg/l	151.7 ± 17.5	10.6 ± 1.4	10.21
NH_4-N	mg/l	22.1 ± 3.1	13.4 ± 0.5	13.60
NO_3-N	mg/l	-	4.9 ± 1.4	5.56
NO_2-N	ml/g	-	1.95 ± 0.75	2.10
pH		7.0 ± 0.08	7.0 ± 0.04	6.98

Table 5: Model validation of the sludge production based on average monthly results for September, 2016.

Parameter	Flow m^3/day	Measured TSS gm/l	Simulated TSS gm/l
Sludge from primary treatment	13,339	7.2	6.9
Sludge from DAF	1,086	30	29.4
Sludge from thickeners	1,581	62	59.3
Sludge from digesters	2,885	34	29.3

The BioWin model was successfully used for creating a plant wide model for Gabal El-Asfar WWTP with accuracy high enough to perform optimization studies later. The optimization of a WWTP is a step-wise process that can result in maximizing the utilization of the available infrastructure with a minimal operating cost while respecting the consistency of the sustainability principles [15]. The validated plant wide model of GAWWTP “contract 19” will be used in a further study to perform several simulations using the influent wastewater data, several runs will be made to study the effect of changing the SRT by changing WAS and RAS on the plant treatment efficiency, nutrients removal, sludge digestion and gas production. Several DO concentrations will be simulated in different aeration tank compartments to decrease aeration costs. Moreover, the effect of temperature will be studied by simulating different heating temperatures in the anaerobic digesters to decrease heating costs. Cost and energy saving from the controlled aeration and the more energy production from the anaerobic digestion is also expected.

4. Conclusion

In this study, modeling applications for a mega WWTP utilizing activated sludge technology was introduced. The BioWin model (Envirosim, Canada) has been used in the performance simulation of Gabal El-Asfar WWTP that receives municipal wastewater. Detailed sampling campaign was performed for accurate wastewater characterization. Seven stoichiometric and kinetic parameters were altered for the model calibration which were: heterotrophic maximum growth rate, heterotrophic decay rate, substrate half saturation, maximum AOB growth rate, AOB decay rate, NH_4 substrate half saturation, and maximum NOB growth rate. The proposed model was successfully and accurately correlated with measurements of COD, ammonia, nitrite, nitrate, TSS MLSS and MLVSS. BioWin model could describe plant operation. BioWin model is a flexible and reliable tool to be used while assessing the performance of centralized mega WWTPs. The validated model will be used in a further study to perform optimization of the WWTP. Cost and energy saving is expected as a result of studying different operational scenarios such as the effect of changing the SRT, the best aeration capacity, and heating in anaerobic digesters.

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